GUTPA/01/05/01

# Light Higgs Boson in the Spontaneously CP Violating NMSSM

**A.T. Davies, C.D. Froggatt and A. Usai**

*Department of Physics and Astronomy*
*Glasgow University, Glasgow G12 8QQ, Scotland*

## Abstract

We consider spontaneous CP violation in the Next to Minimal Supersymmetric Standard Model, without the usual $Z_3$ discrete symmetry. CP violation can occur at tree level, raising a potential conflict with the experimental bounds on the electric dipole moments of the electron and neutron. One escape from this is to demand that the CP violating angles are small, but we find that this entails a light neutral Higgs particle. This is almost pseudoscalar, can have a high singlet content, and will be hard to detect experimentally.

# 1 Introduction

Although the observed lack of CP symmetry is readily accommodated in the Standard Model as a generic feature of the 3x3 CKM matrix, there are other ways in which CP non-conservation can be introduced. Additional sources of CP violation are required to make electroweak baryogenesis viable, and this could be provided by the Higgs sector.

CP can be violated in the Higgs sector either explicitly, through complex coupling constants in the Lagrangian, or spontaneously, when, although the couplings are real, fields acquire complex vacuum expectation values (vevs). It should be acknowledged that spontaneous breaking of CP gives rise to domain walls which cause a cosmological problem, particularly if they are formed relatively late at the electroweak scale. Some suggestions for circumventing this problem have been made [1].

At tree level neither type of CP violation occurs in the Standard Model or the Minimal Supersymmetric Standard Model (MSSM). In the MSSM two or more complex phases can be explicitly introduced in the soft Susy-breaking potential, and at one loop these may give rise to embarrassingly large electric dipole moments for the neutron and electron. It has been shown that cancellations between contributing diagrams can reduce these dipole moments to within experimental bounds in a significant region of the parameter space [2, 3]. However, a recent analysis [4] incorporating new data on mercury atoms suggests that small phases are still required. CP can also be violated spontaneously due to radiative corrections, but because CP is conserved at tree level the CP phases on the Higgs fields are small, and a light almost pseudoscalar particle is predicted [5, 6], in accordance with the Georgi-Pais theorem [7]. This boson is ruled out by LEP experiments [8].

In Susy models the next simplest case is the Next to Minimal Standard Model (NMSSM), in which a gauge singlet scalar field is present in addition to the standard two doublets. In the most commonly discussed version of the NMSSM, which has a discrete $Z_3$ symmetry, Spontaneous CP Violation (SCPV) does not occur at tree level [9]. Breaking can occur by radiative corrections but tends to predict a light scalar as in the MSSM [10].

In a previous paper we considered [11] a more general NMSSM, with no discrete $Z_3$ symmetry, and found that this allows spontaneous CP violation at tree level, without concomitant light neutral bosons. With such a spectrum the CP violating phases are large, and generate large contributions to electric

dipole moments. Cancellations can be arranged so as to be consistent with experiment, but require fine tuning of some soft Susy-breaking terms in the potential.

A more interesting possibility is that CP is spontaneously broken only weakly, in the sense that the phases on the vevs are small. For phases $\lesssim 0.01$ radians the predicted electric dipole moments are suppressed sufficiently even without cancellation [4]. In this case we predicted a light almost purely pseudoscalar boson [12], a result recently confirmed in [13]. Its existence does not follow from the Georgi-Pais theorem but may be understood by a similar argument. We sample the space of unknown coupling parameters and consider the detectability of such a particle. In most cases this particle contains a high proportion of singlet field, which does not couple to gauge bosons or quarks, so it may well escape experimental detection.

After introducing our model we give a qualitative argument for the existence of a light pseudoscalar in the case of weak SCPV. Imposing small CP phases but otherwise relatively little theoretical bias, we randomly sample the large space of unknown parameters and find typical masses and couplings of the Higgs scalars. We then consider the experimental constraints.

## 2 NMSSM

Our model is based on the superpotential

$$W = \lambda N H_1 H_2 - \frac{k}{3} N^3 - rN + \mu H_1 H_2 + W_{Fermion} \tag{1}$$

where $H_1$ and $H_2$ are the doublets of the MSSM and $N$ is a singlet. A possible quadratic $N^2$ term has been removed by a field shift [14]. Traditionally the NMSSM has been studied as a possible solution to the $\mu$-problem of the MSSM. If the N field acquires a vev $x$ of the same scale as those of $H_1$ and $H_2$, then $\lambda x$ in the term $\lambda N H_1 H_2$ provides a $\mu$ of the electroweak scale rather than the GUT scale. We adopt a different viewpoint and regard the NMSSM as just a phenomenological generalisation of the MSSM. We do not impose the usual discrete $Z_3$ symmetry in which $(H_1, H_2, N)$ are rephased by $\exp(i2\pi/3)$, which would require $\mu = r = 0$.

At the electroweak scale the effective potential is [15]

$$V_0 = \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$

$$
\begin{aligned}
&+(\lambda_3+\lambda_4)(H_1^\dagger H_1)(H_2^\dagger H_2) - \lambda_4 \left|H_1^\dagger H_2\right|^2 \\
&+(\lambda_5 H_1^\dagger H_1 + \lambda_6 H_2^\dagger H_2)N^\star N + \lambda_7(H_1 H_2 N^{\star 2} + h.c.) \\
&+\lambda_8(N^\star N)^2 + \lambda\mu(N + h.c.)(H_1^\dagger H_1 + H_2^\dagger H_2) \\
&+m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 N^\star N - m_4(H_1 H_2 N + h.c.) \\
&-\frac{1}{3}m_5(N^3 + h.c.) + m_6^2(H_1 H_2 + h.c.) + m_7^2(N^2 + h.c.) \qquad (2)
\end{aligned}
$$

where the quartic couplings $\lambda_i, i = 1\ldots 8$ at the electroweak scale are related via renormalization group equations to the gauge couplings and the $\lambda, k$ of the superpotential at the supersymmetry breaking scale $M_S$, taken to be 1 TeV. The boundary values at $M_S$ of the quartic couplings are given by

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g_2^2 + g_1^2), \lambda_3 = \frac{1}{4}(g_2^2 - g_1^2), \lambda_4 = \lambda^2 - \frac{1}{2}g_2^2,$$

$$\lambda_5 = \lambda_6 = \lambda^2, \lambda_7 = -\lambda k, \lambda_8 = k^2.$$

The soft Susy-breaking terms $m_i, i = 1\ldots 7$, are taken as phenomenological parameters, without assuming they evolve perturbatively from a more or less universal high energy form. The $m_6^2$ and $m_7^2$ terms are absent in the theory with $Z_3$ symmetry.

The two Higgs doublets and the singlet are expressed in terms of real fields $\phi_i$, (i = 1,2,...,10), through

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \qquad (3)$$

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_4 \\ \phi_7 - i\phi_9 \end{pmatrix},\ H_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_8 + i\phi_{10} \\ \phi_2 + i\phi_5 \end{pmatrix}, N = \frac{1}{\sqrt{2}}(\phi_3 + i\phi_6). \qquad (4)$$

Taking real coupling constants, so that the tree level potential is CP conserving, but allowing complex vevs for the neutral fields,

$$\langle H_i^0 \rangle = v_i e^{i\theta_i} (i = 1, 2), \langle N \rangle = v_3 e^{i\theta_3}, \qquad (5)$$

gives

$$V_0 = \frac{1}{2}(\lambda_1 v_1^4 + \lambda_2 v_2^4) + (\lambda_3 + \lambda_4)v_1^2 v_2^2 + (\lambda_5 v_1^2 + \lambda_6 v_2^2)v_3^2$$

$$+2\lambda_7 v_1 v_2 v_3^2 cos(\theta_1+\theta_2-2\theta_3)+\lambda_8 v_3^4+2\lambda\mu(v_1^2+v_2^2)v_3 cos(\theta_3)$$
$$+m_1^2 v_1^2+m_2^2 v_2^2+m_3^2 v_3^2-2m_4 v_1 v_2 v_3 cos(\theta_1+\theta_2+\theta_3)$$
$$-\frac{2}{3}m_5 v_3^3 cos(3\theta_3)+2m_6^2 v_1 v_2 cos(\theta_1+\theta_2)+2m_7^2 v_3^2 cos(2\theta_3) \qquad (6)$$

where, without loss of generality, $\theta_2 = 0$. As the $m_i$ are unknown we choose five, $m_i$ (i=1,2,3,4,7) to ensure that $V_0$ has a stationary value at prescribed magnitudes and phases $v_1, v_2, v_3, \theta_1, \theta_3$ using the conditions

$$\frac{\partial V_0}{\partial v_i} = 0\,, i = 1, 2, 3 \qquad (7)$$

$$\frac{\partial V_0}{\partial \theta_i} = 0\,, i = 1, 3. \qquad (8)$$

A sixth mass, $m_6$, can be exchanged for the tree level mass of the charged Higgs, $M_{H^+}$, which, using eq. (8) is

$$M_{H^+}^2 \;=\; -\lambda_4 v_0^2 - \frac{2(\lambda_7 v_3^2 \sin(3\theta_3) + m_6^2 \sin\theta_3)}{\sin(2\beta)\sin(\theta_1+\theta_2+\theta_3)}. \qquad (9)$$

This shows how the parameter $m_6^2$, not necessarily positive, and absent in the $Z_3$ symmetric case, introduces extra freedom to raise the charged Higgs mass. This leaves one parameter $m_5$, with no particular interpretation. Fixing $v_0 = \sqrt{v_1^2+v_2^2} = 174$ GeV, we take as parameters $\tan\beta \equiv v_2/v_1$, $R \equiv v_3/v_0$, $\theta_1, \theta_3, M_{H^+}$ and $m_5$. There are also $\lambda, k$ and $\mu$ in the superpotential.

Sets of parameters are chosen which satisfy eqns.(7, 8), and the mass matrix is calculated. Cases with positive mass squared are accepted, as these correspond to a local minimum. The scalar mass-squared matrix is given by

$$M_{ij}^2 = \frac{\partial V_0}{\partial\phi_i\partial\phi_j}\Big|_{\phi=\langle\phi\rangle}\ , (i, j = 1, 10). \qquad (10)$$

The 6x6 neutral block describes 1 zero mass would-be Goldstone boson and 5 massive physical particles, of which 3 are CP even and 2 CP odd when CP is conserved.

# 3 Higgs Spectrum

It has been shown that at tree level the NMSSM with $Z_3$ symmetry and with arbitrary soft terms does not allow SCPV [9]. However, the inclusion of radiative corrections does allow SCPV together with a light boson. Various treatments of the radiative corrections and Susy-breaking potential [10, 16, 17] produce different Higgs spectra, some of which can now be excluded by experiment, but less readily than in the MSSM, due to dilution of couplings by the singlet field. As noticed by Pomarol [18] inclusion of general $Z_3$ symmetry breaking terms does allow SCPV. We have investigated the mass spectrum for the potential of eq.(2) including such terms and found that it is quite possible to produce an experimental spectrum with no light particles [11], but all these solutions had large CP violating phases. Such phases in the NMSSM, as in the MSSM, give rise to large contributions to electric dipole moments. They can be suppressed if the squark masses are several TeV, or if contributions from different diagrams cancel. We have calculated the neutron and electron EDMs choosing the unknown soft parameters at random, and found that very few sets produced the necessary cancellations. We therefore explored further the possibility that the phases are small. In analyses where SCPV is induced by radiative corrections small phases arise naturally and are accompanied by a light scalar, as expected by the Georgi-Pais theorem. In our case SCPV occurs at tree level, so this theorem does not apply. Nevertheless, when we require the phases to be small, and use these as input to fix some parameters in the potential, we find that that there is always a light Higgs particle $h_1$. Figure 1 shows the upper bound on the lightest neutral Higgs mass $M_{h_1}$. Each graph is for a set of values of $\theta_3$ increasing from 0 to $2\theta_1$ where $\theta_1$ is fixed at 1, 0.1, 0.01 and 0.001 radians. For each $\theta_1, \theta_3$ we randomly selected 100,000 sets of the other parameters with values in the following ranges: $2 \leq \tan\beta \leq 3$, $10 \leq v_3 \leq 510$ GeV, $-500 \leq m_5 \leq 500$ GeV, $-500 \leq \mu \leq 500$ GeV, $55 \leq M_{H^\pm} \leq 800$ GeV and $\lambda = k = 0.5$.

These figures and those below correspond to local minima, but experience suggests that, given enough computer time, global minima could be found giving masses not far below these bounds. Such graphs show that the upper bound when $\theta_1$ and $\theta_3$ are small ($\lesssim 0.1$ radians) is roughly $M_{h_1} \simeq \frac{\min(\theta_1,\theta_3)}{0.01}\, 5$ GeV.

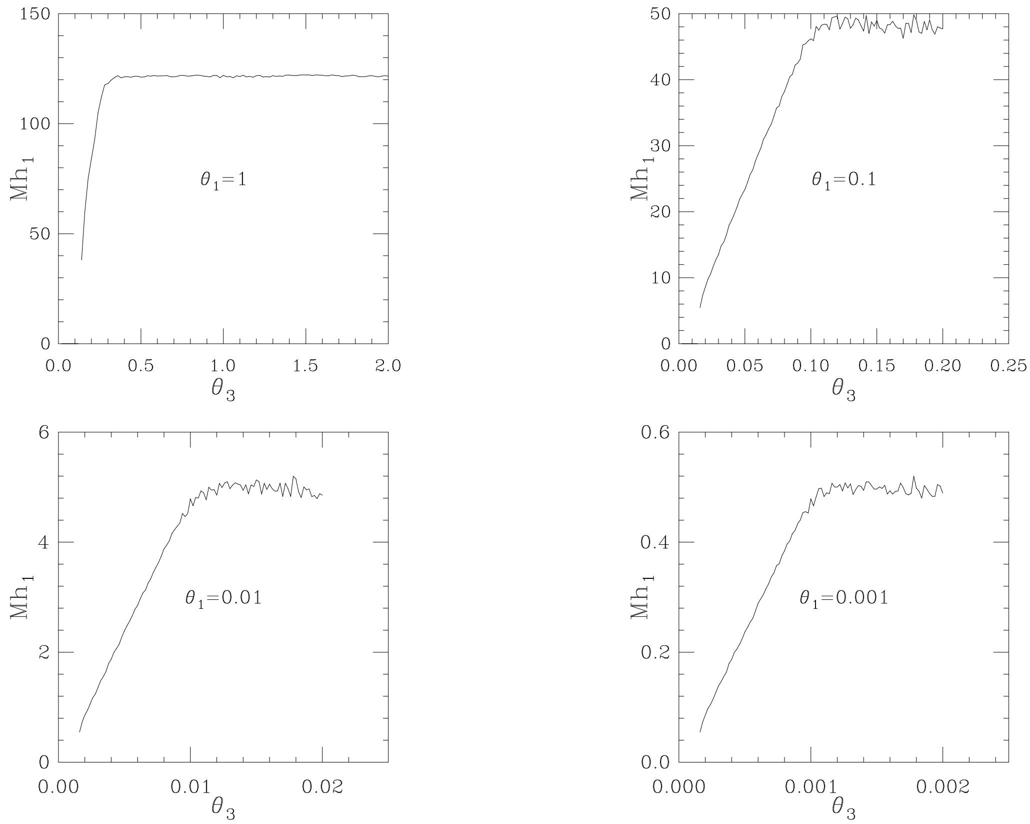


Figure 1: Upper bound on the lightest neutral Higgs mass $M_{h_1}$ as a function of $\theta_3$, for $\theta_1$ equal to 1, 0.1, 0.01 and 0.001 radians respectively and with Susy breaking scale $M_S = 1$ TeV.

# 4 Light Higgs

The result that weak spontaneous CP breaking implies a light Higgs particle is quite general, and may be understood by a variant on the argument of Georgi and Pais [7].

The central step in the proof of the Georgi-Pais theorem is the equation

$$\sum_k \frac{\partial^2 V_o}{\partial \phi_j \partial \phi_k} \left((U\delta\lambda)_k - \delta\lambda_k\right) = 0, \tag{11}$$

where $V_o(\phi)$ is the field dependent scalar potential, $\phi_j$ are spinless boson

fields, the vector $\lambda$ is the value of $\phi$ at which the minimum of the scalar potential occurs, U is the CP symmetry operator and $\delta\lambda$ is the change due to radiative corrections. If there is no spontaneous symmetry breaking, $U\lambda = \lambda$ and from eq.(11) it is clear that, if the mass matrix $\partial_j \partial_k V_0$ is not singular, the relation $U\delta\lambda = \delta\lambda$ holds and no SCPV occurs. On the other hand if a massless particle is present in the unbroken theory then the mass matrix is singular and SCPV may be induced by the radiative corrections. The massless mode will gain a small mass as a result of the radiative corrections. It is this mechanism which produces the light particle when SCPV is induced in the MSSM or the NMSSM with the $Z_3$ discrete symmetry.

The key assumption is that the breaking is perturbative. We make a corresponding assumption, in the general NMSSM model without $Z_3$ symmetry, that there is a SCPV minimum with small phases and that the effective potential can be expanded as a Taylor series about this point. For small CP violating phases the potential of eq.(2) has CP conjugate minima at the points

$$\underline{\epsilon}_1 = (v_1, v_2, v_3, v_1\theta_1, v_2\theta_2, v_3\theta_3), \tag{12}$$

$$\underline{\epsilon}_2 = (v_1, v_2, v_3, -v_1\theta_1, -v_2\theta_2, -v_3\theta_3) \tag{13}$$

in a basis of $(ReH_1^0, ReH_2^0, ReN, ImH_1^0, ImH_2^0, ImN)$. Performing a Taylor expansion of $\frac{\partial V}{\partial \phi_i}$ about $\underline{\phi} = \underline{\epsilon}_1$

$$(\epsilon_2 - \epsilon_1)_j \frac{\partial^2 V}{\partial \phi_j \partial \phi_i}\Big|_{\underline{\epsilon}_1} \approx \frac{\partial V}{\partial \phi_i}\Big|_{\underline{\epsilon}_2} - \frac{\partial V}{\partial \phi_i}\Big|_{\underline{\epsilon}_1} = 0 - 0, \tag{14}$$

we see that to leading order the mass squared matrix must be singular. To this order there is a zero mass particle, with eigenvector along the direction $\underline{\epsilon}_2 - \underline{\epsilon}_1$ in the 6-dimensional neutral Higgs space joining the two CP violating minima. If $\theta_i \neq 0$, the neutral matrix does not decouple into sectors with CP = +1 and -1, but it does so approximately, as the off diagonal blocks of the matrix are proportional to the small angles $\theta_i$. To this approximation, the light particle is always in the matrix block corresponding to imaginary parts of the fields and so is almost purely CP odd. Depending on the parameters in the potential, this particle can be a varying admixture of singlet and doublet fields.

This is most easily examined by changing to the unitary gauge. In the limit of zero phases, the matrix reduces to a 3x3 block of the real parts of

the fields and a 2x2 block of the imaginary parts of fields of the form

$$\begin{pmatrix} \frac{A}{\sin\beta\cos\beta} & \frac{v_0}{v_3}B \\ \\ \frac{v_0}{v_3}B & C \end{pmatrix} \tag{15}$$

where A is the (5,4) element of the whole 6x6 mass matrix, B is equal to $\frac{v_2}{v_3}$ times the (6,4) element, and C is equal to the (6,6) element. In the matrix of eq.(15) the (1,1) element is doublet and the (2,2) element is singlet.

The condition for a massless pseudoscalar is obviously

$$\frac{AC}{\sin\beta\cos\beta} = (\frac{v_0}{v_3}B)^2. \tag{16}$$

When the phases are not zero but small, this particle becomes light and almost-pseudoscalar. We can readily see how the nature of the light particle depends on $\theta$. For example, if $\theta_1 << \theta_3$ the eigenvector $\underline{\epsilon}_2 - \underline{\epsilon}_1$ is in the singlet direction, and the massless particle is pure singlet. In this case eq.(8) just gives B = A = 0 , and so eq.(16) is satisfied with $C \neq 0$. Likewise for $\theta_3 << \theta_1$ eq.(8) gives B = C = 0 and the light particle is pure doublet. In general the N field percentage in the light pseudoscalar eigenvector is

$$N\% \simeq \frac{100\, v_3^2\, \theta_3^2}{v_0^2\, \sin^2\beta\, \cos^2\beta\, \theta_1^2 + v_3^2\, \theta_3^2} \tag{17}$$

which is small if $v_3\theta_3 << v_0\theta_1$. For high values of $v_3$ such that $v_0$ can be neglected, the N field fraction will be independent of $\theta_3$ and $v_3$ and equal to 1. It is significant for the experimental detectability that the fraction of singlet is naturally high, even for quite moderate values of the parameters. For example, tan$\beta$ = 1, $v_3 = v_0$, $\theta_1 = \theta_3$, gives N% = 80%, and tan$\beta$=2, $v_3 = 2\, v_0$, $\theta_1 = \theta_3$ gives a light pseudoscalar which is 96% singlet.

The result that small phases imply a light particle is not specific to the NMSSM. It is more transparent in a general 2 doublet model with no explicit CP violation, with doublets $\Phi_1$ and $\Phi_2$, where we need keep only one SCPV phase $\theta$ and analytical formulae can be given for all tree level masses. In such a model with a discrete $Z_2$ symmetry $\Phi_1 \to -\Phi_1, \Phi_2 \to \Phi_2$, the equation for a stationary value of the effective potential is

$$\sin\theta(2\lambda_5 v_1 v_2 \cos\theta - m_{12}^2) = 0, \tag{18}$$

where $m_{12}^2\Phi_1^\dagger\Phi_2$ and $\lambda_5(\Phi_1^\dagger\Phi_2)^2$ are terms in the potential. So as well as the CP conserving solution

$$\sin\theta = 0\,, \tag{19}$$

there is the SCPV one at $\pm\theta$, where

$$\cos\theta = \frac{m_{12}^2}{2\lambda_5 v_1 v_2}. \tag{20}$$

The mass of the pseudoscalar A when $\theta = 0$ is

$$M_A^2 = v_0^2\left(\frac{m_{12}^2}{2v_1v_2} - \lambda_5\right), \tag{21}$$

and is a continuous function of $\theta$ in the SCPV case. So we see from eq.(20) that small $\theta$ implies a low mass $M_A$. On the other hand, the CP conserving eq.(19) does not imply a zero mass particle. In the MSSM $\lambda_5 = 0$ at tree level and $m_{12}^2$ is a free parameter, which can be large. Radiative corrections generate a small $\lambda_5$ [5], and SCPV becomes possible, but, as shown by eq.(20), only if $\frac{m_{12}^2}{2v_1v_2}$ is also small.

Here the equations are identical to the classical dynamics problem of a bead free to slide on a vertical circular wire, radius $a$, constrained to rotate about its vertical diameter at constant angular velocity $\omega$. For small $\omega$ the stable equilibrium position is $\theta = 0$ but if $\omega$ exceeds a critical value $\sqrt{\frac{g}{a}}$ the stable equilibrium is at $\theta \neq 0$. The angular frequency of oscillation about this position is $p = \omega\,\sin\,\theta$, which tends to zero for small $\theta$. Oscillations about the stable $\theta = 0$ position have $p = \sqrt{(\frac{g}{a} - \omega^2)}$, which tends to zero at the critical $\omega$ but can be large near $\omega = 0$.

These examples clarify how in the NMSSM case small $\theta$ implies a light particle, but $\theta = 0$ need not. They also bring out the point implicit in our approximate argument that there are no large parameters in the problem. In the dynamics case there would be no low frequency mode if $\omega$ were $O(\theta^{-1})$. In the NMSSM the argument breaks down if the vev ratio $v_3/v_0$ is very large.

# 5 N field and second lightest neutral Higgs boson for small phases

In the results presented below and in Fig.1, we have diagonalized the full 6x6 neutral mass squared matrix numerically. We have then made an orthogonal

transformation to isolate the Goldstone mode, in order to look at the eigenvectors of the 5 physical particles $h_i$, to determine their field content and to obtain the $ZZh_i$ and $Zh_ih_j$ couplings.

The first important result is that described in Section 4: the existence of a light particle $h_1$ when the phases are small enough to naturally generate electron and neutron dipole moments consistent with experiment. Its eigenvector is almost entirely composed of the imaginary parts of the doublet $H_1$, $H_2$ and singlet N fields. The percentage of singlet in the eigenvector of $h_1$ is high in general, as can be seen in Fig. 2. The exact N field percentage depends on the value of $v_3/v_0$. This is correlated with the value of $M_{H^+}$. Although these parameters are independently specified, it is found that the condition that all masses are real forces $M_{H^+}$ and $v_3$ to increase together. This favours a high singlet content, which is crucial as far as possible experimental detection of the pseudoscalar $h_1$ is concerned.

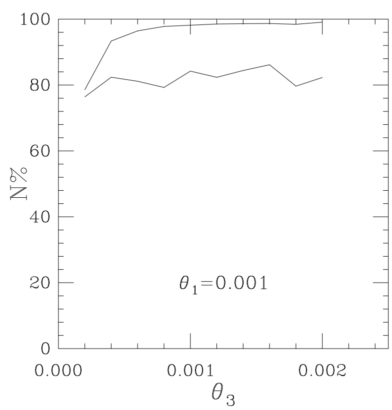


Figure 2: N field percentage in the eigenvector of the lightest neutral Higgs boson for $M_{H^\pm}$=200-800 GeV (upper line) and $M_{H^\pm}$=55-200 GeV (lower line) for $\theta_1$=0.001, $\theta_3 = 0 - 2\theta_1$.

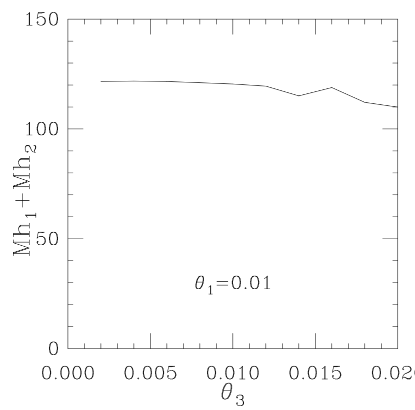


Figure 3: The sum of the masses of the two lightest neutral Higgs bosons $M_{h_1}+M_{h_2}$ as a function of $\theta_3$, with $\theta_1$=0.01 radians, $M_{H^\pm}$=55-200 GeV and $M_S$=1 TeV.

The second lightest neutral Higgs boson $h_2$ is always nearly pure scalar and is mainly doublet in the region of the parameter space where $v_3$ and

$M_{H^\pm}$ are large compared to $v_0$: it could therefore be visible in future experiments. Furthermore, the sum of the masses of the lightest and second lightest neutral Higgs bosons has an upper bound of about 120 GeV as shown in Fig.3. In these graphs radiative corrections have been incorporated using the Standard Model renormalisation group equations between $M_S = 1$ TeV and the electroweak scale $v_0 = 174$ GeV, for $\tan\beta$ between 2 and 3. These radiative corrections correspond to having degenerate stops with a mass of $M_S = 1$ TeV and are significant for the nearly pure scalar mass $M_{h_2}$.

# 6 Experimental Signature

One might think that a light boson such as we predict has been ruled out by experiment, but this is not so. Our light particle is difficult to detect for two reasons. In the first place it is almost purely CP odd, and there is no ZZA coupling, where A denotes a CP=-1 particle; S will be used for one with CP=+1. A ZA state can not be produced at LEP, for real or virtual Z, but associated production of SA is possible if kinematically allowed. This was not seen at LEP, possibly because the ZSA coupling was small. In the MSSM the ZZS coupling is complementary to the ZSA coupling so that non production of ZS allows LEP2 to exclude $M_A \leq 80$ GeV, $M_S \leq 80$ GeV [8]. Within the MSSM, therefore, experiment excludes a light pseudoscalar. This complementarity argument does not apply to a general 2 doublet model or to the NMSSM. The second obstacle to detection is that the light near-pseudoscalar can be mainly singlet, and a singlet does not couple to gauge fields, quarks or leptons at tree level, only to the other Higgs particles. The singlet component will not contribute to $\Upsilon$ decays by the Wilczek process, and thus with N% $\gtrsim$ 90% and $\tan\beta \lesssim 3$ the lower limits [19] on the mass of a pseudoscalar can be evaded. To get a more quantitative idea of the experimental detectability, we have calculated the production cross section of all the Higgs bosons at LEP2 energies. Each set of parameters gives definite tree level masses and couplings for all the Higgs particles. We have not attempted a Monte Carlo analysis, in view of the uncertainties and complexities of decay modes and detector efficiencies. Following the spirit of one of the few analyses based on the NMSSM [20], we arbitrarily assume that if the cross section in any production channel $Zh_i$ or $h_ih_j$ was as large as 0.3 pb, corresponding to 20 events at LEP2 luminosity of 175×4 pb$^{-1}$ at 200 GeV,

a signal would have been detected. Although for $\theta_1$ and $\theta_3 < 0.1$ all our parameter sets gave a neutral Higgs boson of mass <50 GeV, we could always find regions of the ($M_{H^\pm}$, $v_3$, $m_5$, $\mu$, $\tan\beta$) space in which this particle and its partners are undetectable at LEP, except for $\theta_3 << \theta_1$ where the particle is mainly doublet.

# 7 Conclusions

Spontaneous CP violation is possible in the NMSSM at tree level. It can give an acceptable Higgs spectrum. If the phases on the vevs are small, there is a light particle, predominantly pseudoscalar, and predominantly singlet in much of the parameter space, and thus hard to detect. Phases $\theta_{1,3} = \mathcal{O}(0.01)$, such as may be required to suppress electric dipole moments, give a mass $M_{h_1} \lesssim \frac{\min(\theta_1,\theta_3)}{0.01}$ 5 GeV. This model is not yet ruled out but will be open to more stringent tests at higher energy colliders such as the LHC, where all 5 neutral Higgs bosons should be kinematically accessible and their couplings cannot all be predominantly singlet.

# Acknowledgements

We would like to thank D.G. Sutherland for discussions. This work was supported in part by PPARC and the EU TMR Network contract FMRX-CT97-0122.

# References

[1] L.M. Krauss and S.J. Rey, *Phys. Rev. Lett.* **69**, (1992), 1308

[2] T. Ibrahim and P. Nath, *Phys. Rev.* D **57**, (1998), 478.

[3] M. Brhlik, G J. Good and G.L. Kane, *Phys. Rev.* D **58**, (1999), 115004.

[4] S. Abel, S.Khalil, and O. Lebedev, hep-ph/0103320.

[5] N. Maekawa, *Phys. Lett.* B **282**, (1992), 392.

[6] A. Pomarol, *Phys. Lett.* B **287**, (1992), 331.

[7] H. Georgi and A. Pais, *Phys. Rev.* D **10**, (1974), 1246.

[8] P. Gay, *Proc. of Int. Europhysics Conference on High Energy Physics*, Tampere, 1999, Eds. K. Huito, H. Kurki-Suonio, J. Maalampi, IoP.

[9] J.C. Romão, *Phys. Lett.* B **173**, (1986), 309.

[10] K.S. Babu and S.M. Barr, *Phys. Rev.* D **49**, (1994), R2156.

[11] A.T. Davies, C.D. Froggatt and A. Usai, *Proc. of the International Europhysics Conference on High Energy Physics*, Jerusalem (1997), Eds. D. Lellouch, G. Mikenberg and E. Rabinovici , Springer-Verlag (1998),p891.

[12] A.T.Davies, C.D. Froggatt and A. Usai, *Proc. of Conference on Strong and Electroweak Matter, Copenhagen* (1998), Eds. J. Ambjorn, P.H. Damgaard, K. Kainulainen, K. Rummukainen, World Scientific (1999), p227.

[13] G.C. Branco, F. Krũger, J.C. Romão, A. Teixeira, hep-ph/0012318.

[14] J.F. Gunion, H.E. Haber, *Nucl. Phys.* B **272**, (1986), 1.

[15] J.F. Gunion, H.E. Haber, G. Kane, S. Dawson, The Higgs Hunter's Guide, (Addison-Wesley, Reading MA, 1990).

[16] N. Haba, M. Matsuda and M. Tanimoto, *Phys. Rev.* D **54**, (1996), 6928.

[17] H.M. Asatrian, G.K. Eguian, Mod. Phys. Lett. A10, (1995), 2943.

[18] A. Pomarol, *Phys. Rev.* D **47**, (1993), 273.

[19] M. Krawczyk, hep-ph/0103223.

[20] S. F. King and P. L. White, *Phys. Rev.* D **53**, (1996), 4049.